

# The correlations between the twin kHz QPO frequencies of LMXBs

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## ABSTRACT

We analyzed the recently published kHz QPO data in the neutron star low-mass X-ray binaries (LMXBs), in order to investigate the different correlations of the twin peak kilohertz quasi-periodic oscillations (kHz QPOs) in bright Z sources and in the less luminous Atoll sources. We find that a power-law relation  $\nu_1 \sim \nu_2^b$  between the upper and the lower kHz QPOs with different indices:  $b \simeq 1.5$  for the Atoll source 4U 1728-34 and  $b \simeq 1.9$  for the Z source Sco X-1. The implications of our results for the theoretical models for kHz QPOs are discussed.

**Key words:** accretion: accretion disks – stars:neutron – binaries: close – X-rays: stars

## 1 INTRODUCTION

With the advent of the Rossi X-ray Timing Explorer (*RXTE*), our knowledge of the properties of the aperiodic variability of neutron star (NS) low mass X-ray binaries (LMXBs) took a substantial step forward, especially initiated by the discovery of the kilohertz quasi-periodic oscillations (kHz QPOs) in about twenty more LMXBs (see van der Klis 2000, 2004, for a review). The kHz QPOs in the power spectra of these systems cover the range of frequency from some hundred Hz to more than one kHz, and they often occur in pairs in the persistent emission: the upper kHz QPO frequency ( $\nu_2$ , hereafter the upper-frequency) and the lower kHz QPO frequency ( $\nu_1$ , hereafter the lower-frequency). The kHz QPOs were soon found to behave in a rather regular way and the study of their phenomenology led to the discovery of tight correlations between their frequencies and other observed characteristic frequencies (see, e.g., Psaltis et al. 1998, 1999a; Stella et al. 1999; Belloni et al. 2002). Without any doubt, *RXTE* has provided a probe into the accretion flow in the non-Newtonian strong gravity regime where Einstein's General Relativity might be tested (van der Klis 2000, 2004).

The correlation between the upper-frequency and the lower-frequency across different sources or for a particular source, such as Sco X-1, can be roughly fitted by a power law function (see, e.g., Psaltis et al. 1998, 1999a), but also by a linear model (see Belloni et al. 2005). The kHz QPO peak separation  $\Delta\nu \equiv \nu_2 - \nu_1$  between the upper-frequency and lower-frequency in a given source is generally inconsistent with a NS spin frequency. In some sources,  $\Delta\nu$  is lower or higher than the NS spin frequency (when directly measured, see e.g. Méndez & van der Klis 1999; Jonker, Méndez, & van der Klis 2002b) or than the nearly coherent oscillation frequency ( $\nu_{\text{burst}}$ ) observed during type I X-ray burst that is identified to be the stellar spin frequency (Muno 2004; Strohmayer & Bildsten 2003; Wijnands et al 2003; van der Klis 2004). The averaged

peak separations are found to be either close to (but not consistent with) the spin frequency  $\nu_s$  or to its half  $\nu_s/2$  (see, e.g., Wijnands et al. 2003; van der Klis 2004; Lamb & Miller 2001). The above observations offer strong evidence against the simple beat-frequency model, in which the lower-frequency is the beat between the upper-frequency and the NS spin frequency  $\nu_s$  (see e.g. Strohmayer et al. 1996; Zhang et al. 1997; Miller et al. 1998), i.e.  $\nu_1 = \nu_2 - \nu_s$ . Nonetheless, with the discovery of pairs of 30–450 Hz QPOs from a few black-hole candidates with frequencies ratios 3:2 (see, e.g., van der Klis 2004), Abramowicz et al. (2003ab) reported that the ratios of twin kHz QPOs in Sco X-1 tend to cumulate around a value of 3:2, and they interpreted it as an evidence of a near  $\sim 3:2$  resonance. This was further argued by Abramowicz et al. (2003ab) to be a promising link with the black-hole high-frequency QPOs (see e.g. van der Klis 2004). Moreover, the production mechanisms of kHz QPOs are still open issues: they have been identified with various characteristic frequencies in the inner accretion flow (see e.g. Stella & Vietri 1999; Titarchuk et al. 1998; Titarchuk & Osherovich 2000; Psaltis & Norman 2000; Lamb & Miller 2001; Zhang 2004).

In this paper, in order to check the predictions of the kHz QPO models, we analyze the recently published kHz QPO data by *RXTE*, which have been used by several authors (see, e.g., Belloni et al. 2005; Méndez & van der Klis 1999, 2000; Psaltis et al. 1998, 1999a; van der Klis 2000, 2004, and original references therein). Most of the data are provided by T. Belloni, M. Méndez and D. Psaltis, and the others are extracted from the references listed in Table 1. Therefore, the data we analyzed here constitute a larger sample than that presented by Belloni et al. (2005). In section 2, we critically discuss the twin kHz QPO correlation. The conclusions and discussions are given in the last section.

## 2 THE CORRELATIONS BETWEEN THE TWIN KHZ QPOS

Figure 1 shows various correlations of the twin kHz QPOs, such as  $\nu_1$  vs.  $\nu_2$ ,  $\Delta\nu$  vs.  $\nu_2$  and  $\nu_2/\nu_1$  vs.  $\nu_2$ , obtained using the simultaneously detected twin kHz QPO data of LMXBs listed in Table 1. We fitted power-law relation,

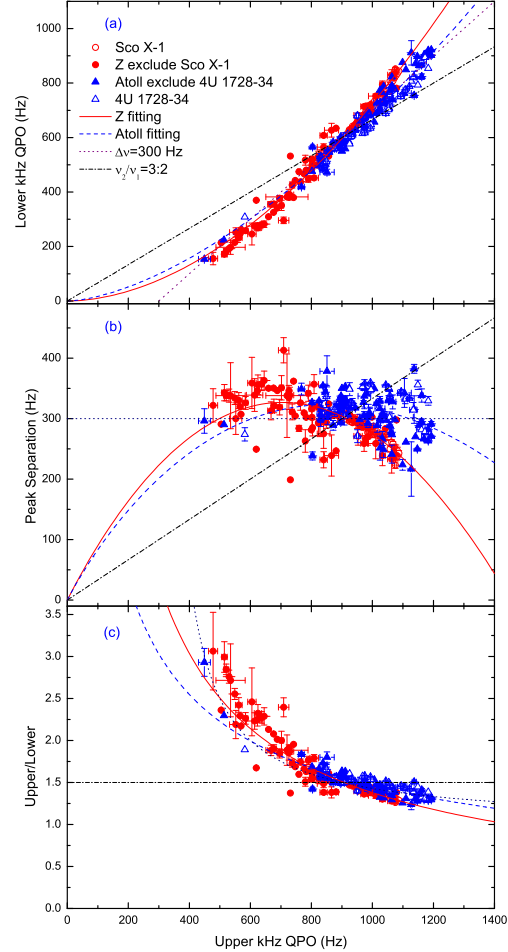
$$\nu_1 = a \left( \frac{\nu_2}{1000 \text{ Hz}} \right)^b \text{ Hz}, \quad (1)$$

for the kHz QPO samples of Atoll and Z sources separately. A similar relation was discussed by Psaltis et al. (1998), with a smaller set of QPO data points for Sco X-1. The normalization coefficient  $a$  and the power-law index  $b$  for various cases are listed in Table 2. We find that the  $\nu_1$  vs.  $\nu_2$  correlations for the Atoll source 4U 1728-34 and the Z source Sco X-1 are somewhat distinct in their power-law indices,  $\sim 1.5$  and  $\sim 1.9$ , respectively. Furthermore, for different ranges of  $\nu_2$  in Z sources (i.e.  $\nu_2 < 840$  Hz and  $\nu_2 > 840$  Hz), we obtain different normalization coefficients and power-law indices (i.e. 2.20 and 1.79). However, the  $\chi^2$  test in figure 2a seems not to favor this broken power-law correlation because of the slightly larger  $\chi^2$ -values. Figure 2a shows  $\chi^2$  tests that correspond to the relation (1), where in many cases the minimum  $\chi^2$ -values are larger than  $\sim 3.0$  for the Z and Atoll samples, relatively too high values consider them good fits. However, using only the data points for Sco X-1 and 4U 1728-34, the minimum  $\chi^2$ -values for relation (1) become  $\simeq 0.6$  and  $\simeq 0.9$  respectively, less than the corresponding value  $\sim 2$  for Sco X-1 previously obtained by Psaltis et al (1998). Therefore, for the individual Z or Atoll sources Sco X-1 and 4U 1728-34, we obtain power-law correlations between the kHz QPOs with different normalization coefficients power-law indices between the two sources. The choice of a power-law relation to describe the kHz QPO data is arbitrary. Other functional forms can also fit the data equally well, as the linear correlation adopted by Belloni et al. (2005) with a smaller sample of QPO data. If relation Eq.(1) is valid, it implies a non-monotonic change of the peak separation, with a maximum at an upper kHz QPO frequency of  $\sim 700$  Hz, as shown in Figure 1b.

### 2.1 Testing the constant twin peak separation

In fact, it is not just for Sco X-1 (van der Klis et al 1997; Méndez & van der Klis 2000) that the peak separation is known to be not constant but also for other Z sources, e.g., GX 17+2 (Homan et al. 2002), GX 340+0 (Jonker et al. 2000) and GX 5-1 (Jonker et al. 2002a), and for several Atoll sources, e.g., 4U 1728-34 (Migliari, van der Klis, & Fender 2003; Méndez & van der Klis 1999), with  $\Delta\nu$  always significantly lower than the burst oscillation frequency  $\nu_{\text{burst}}$ , 4U 1636-53 (Jonker, Méndez, & van der Klis 2002b; Méndez, van der Klis, & van Paradijs 1998b) with  $\Delta\nu$  varying between being lower and higher than  $\nu_{\text{burst}}/2$ , 4U 1608-52 (Méndez et al. 1998c) and 4U 1735-44 (Ford et al. 1998), etc.

In order to test the hypothesis of a constant peak separation between the twin kHz QPOs, we inspect our sample of simultaneously detected twin kHz QPOs over a wide range of frequencies separately for Atoll sources (110 pairs) and Z sources (158 pairs). In figure 1b, we show that the peak separation in individual Atoll or Z sources, as for instance Sco X-1 and 4U 1728-34, decreases systematically with increasing upper frequency if  $\nu_2$  is larger than  $\sim 700$  Hz, a fact that has been reported in the literatures before (see, e.g. van der Klis 2000, 2004 for recent reviews). Figure 2b shows the results of a  $\chi^2$  test against a constant peak separation of twin kHz QPOs in Atoll and Z sources. The resulting minimum

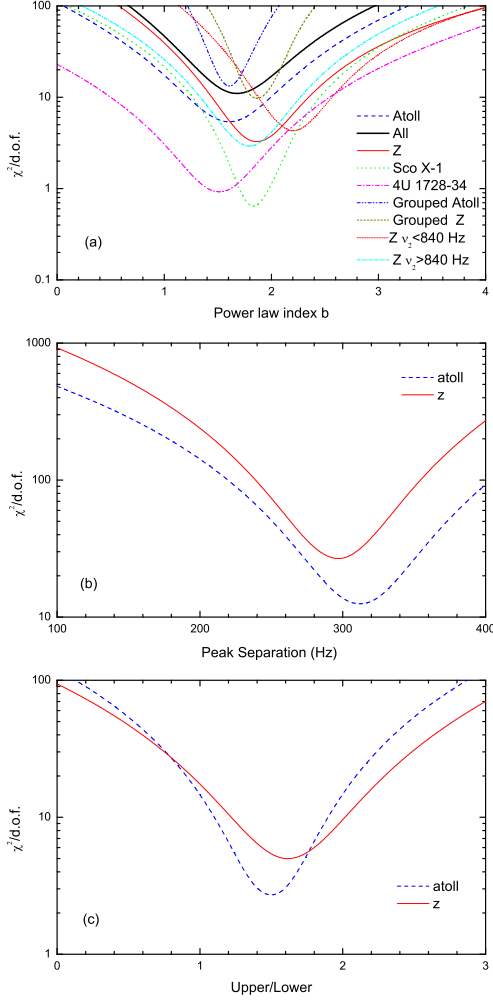


**Figure 1.** Plots of (a)  $\nu_1$  vs.  $\nu_2$ , (b)  $\Delta\nu$  vs.  $\nu_2$  and (c)  $\nu_2/\nu_1$  vs.  $\nu_2$ . The Z [Atoll] fitting line represents the fitted correlation between the pair kHz QPO frequencies for the Z [Atoll] sources as  $\nu_1 = (724.99 \pm 2.52 \text{ Hz})(\nu_2/1000\text{Hz})^{1.86 \pm 0.03}$  [ $\nu_1 = (683.48 \pm 3.01 \text{ Hz})(\nu_2/1000\text{Hz})^{1.61 \pm 0.04}$ ].

$\chi^2$ -values are very high, and we therefore conclude that there is not a constant peak separation either for Z sources or Atoll sources. Nevertheless, this also confirms the previously known result that the Sco X-1 data are inconsistent with a constant peak separation (see also van der Klis et al. 1997; Psaltis et al. 1998; Méndez & van der Klis 2000).

### 2.2 Testing a preferred 3:2 ratio in the twin kHz QPOs

From Figure 1b, one can see that a constant ratio relation  $\nu_2 = (3/2)\nu_1$ , shown as a dash-dotted line, is not consistent with the observed data. Moreover, Figure 1c shows that the frequency ratio systematically decreases from 3.2 to 1.2 with increasing the kHz QPO frequency. As a further investigation, we also performed a  $\chi^2$  test against a constant ratio, shown in figure 2c. The obtained  $\chi^2$ -values are too high to confirm a 3:2 peak ratio for the all kHz QPO data. In addition, the incompatible 3:2 ratio peak distribution has been also studied by Belloni et al. (2005) for many sources:

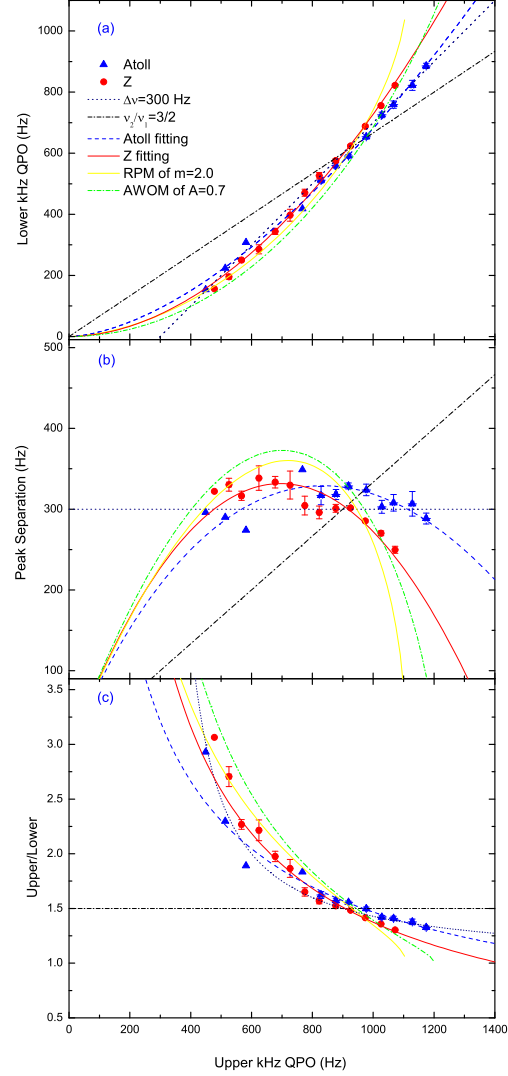


**Figure 2.** Chi-square tests for (a) the hypothesis of a power-law correlation, (b) a constant peak separation and (c) a constant ratio between the twin kHz QPOs of LMXBs listed in Table 1.

they showed that the distribution of QPO frequencies in Sco X-1, 4U 1608–52, 4U 1636–53, 4U 1728–34, and 4U 1820–30 is multi-peaked, with the peaks occurring at the different  $\nu_2/\nu_1$  ratios, not all ratios appearing in all sources.

### 2.3 Testing other kHz QPO models

In order to account for a variable peak separation of twin kHz QPOs, some viable models have been proposed. The variable peak separation was predicted in the relativistic precession model (Stella & Vietri 1999) and the Alfvén wave oscillation model (Zhang 2004), where for both models the upper-frequency was ascribed to the Keplerian orbital frequency, while the lower-frequency was ascribed to the periastron precession frequency and the Alfvén wave oscillation frequency, respectively. In Figure 1, the QPO data points are scattered, which makes it difficult to estimate the kHz QPO relations by reading the figure directly. In order to compare clearly the models with the trends of twin kHz QPOs, we divided all data points into 50 Hz bins, and then averaged the quantities in every



**Figure 3.** The panels are the same as for Figure 1. For reason of clarity, we divided all kHz QPO data into bins of 50 Hz interval in  $\nu_2$ , and then average the corresponding kHz QPO data in each bin. The Z (Atoll) fitting line represents the fitted correlation between the twin kHz QPOs for grouped Z (Atoll) samples as  $\nu_1 = (727.88 \pm 6.63 \text{ Hz})(\nu_2/1000\text{Hz})^{1.91 \pm 0.05}$  ( $\nu_1 = [681.42 \pm 5.39 \text{ Hz}][\nu_2/1000\text{Hz}]^{1.65 \pm 0.05}$ ). AWOM (RPM) is the theoretical curve of the model by Zhang (2004) with the averaged stellar mass density parameter  $A=0.7$  (by Stella & Vietri [1999] with the mass parameter  $m=2.0 M_\odot$ ).

bin. We plot these group-averaged values in Figure 3, with the same panels as Figure 1. We point out that neither the relativistic precession model nor the Alfvén oscillation model can explain the distinctions of kHz QPOs for both the Atoll and Z sources, even though both models are in good agreement with the observed kHz QPO data, as shown in Figure 3, once the model parameters are tuned.

The motivation for performing a 50 Hz binning to discuss the twin kHz QPO correlations was that we want to show the averaged effects. The dispersions of the averaged data points are bigger than their averaged error bars (Figure 3), so the minimum  $\chi^2$ -value corresponding to each group is usually much larger than 1.0. There-

fore, we remark that their error bars underestimate the true uncertainties, and the calculations show that the minimum  $\chi^2$ -values for the fitted lines of the grouped samples, as shown in the caption of Figure 3, are also too high for the fits to be acceptable.

### 3 CONCLUSIONS AND DISCUSSIONS

We have analyzed an updated sample of frequencies of the simultaneously detected twin kHz QPOs in LMXBs. Our main conclusions are the following. (1) The power-law correlations were analyzed by means of  $\chi^2$  tests: the sources 4U 1728-34 and Sco X-1 are found to yield good power-law fits, with minimum  $\chi^2$ -values lower than 1. The power-law indices are  $b \simeq 1.5$  for the Atoll source 4U 1728-34 and  $b \simeq 1.9$  for the Z source Sco X-1. A similar power-law index was previously obtained with a slightly high minimum  $\chi^2$ -value  $\sim 2$  by Psaltis et al. (1998). As it is known, Atoll and Z sources show distinct properties in their spectra and luminosity (Hasinger & van der Klis 1989; van der Klis 2000), and we do not yet know what properties cause the differences in their power-law indices. Nevertheless, if the power-law relations with different indices for Atoll and Z sources are confirmed by future detections, then any kHz QPO models discarding the distinctions of the Atoll and Z sources will confront severe arguments. (2) Clearly, obeying such a power-law relation would contradict the constant peak separation and constant (3:2) peak ratio between kHz QPOs, and in fact the plotted curves in Figure 1 and Figure 3 are incompatible with these constant relations. These conclusions have been previously inferred with smaller samples of kHz QPO data (see, e.g. Psaltis et al. 1998; Psaltis et al. 1999ab; Belloni et al. 2005), but contrary to the suggestions by the simple beat model and any model that predict  $\Delta\nu=\text{constant}$  and  $\nu_2 = (3/2)\nu_1$ , respectively. In addition, based on the updated kHz QPO data of LMXBs we find that there is no extremely sharp concentration at a 3:2 peak ratio as indicated by the  $\chi^2$  test in Figure 2c; the ratios are broadly distributed from  $\sim 1.2$  to  $\sim 3.2$  over a frequency range of some hundred Hz, as shown in Figure 1c. Therefore, the non-linear resonance model (see e.g. Abramowicz et al. 2003b; Rebusco 2004) can be consistent with this distribution of peak ratios. Nevertheless, it is shown in Figure 1c that the value of  $\nu_2/\nu_1$  decreases systematically with increasing QPO frequency. (3) In a rough approximation, the kHz QPO frequency correlation seems to be consistent with the predictions by the model based on the basic general relativistic frequencies around a compact object (Stella & Vietri 1999) and those by the model based on the Alfvén wave oscillation (Zhang 2004), with properly selected parameters. Both models predicted a peak separation decreasing with increasing QPO frequency, but increasing when the upper frequency is low, for instance less than  $\sim 700$  Hz. Therefore, more kHz QPO detections are needed to confirm the predictions of the models. In conclusion, if future data still support the conclusions obtained in the paper, they will pose new constraints on models for explaining kHz QPOs.

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**Table 2. The twin kHz QPO correlation  $\nu_1 = a(\nu_2/1000\text{Hz})^b$**

Sources*	$a$ (Hz)	$b$
All Z samples	$724.99 \pm 2.52$	$1.86 \pm 0.03$
Z ( $\nu_2 < 840$ Hz)	$812.09 \pm 2.59$	$2.20 \pm 0.10$
Z ( $\nu_2 > 840$ Hz)	$722.72 \pm 1.45$	$1.79 \pm 0.03$
Sco X-1	$721.95 \pm 0.69$	$1.85 \pm 0.01$
All Atoll samples	$683.48 \pm 3.01$	$1.61 \pm 0.04$
4U 1728-34	$667.86 \pm 5.59$	$1.51 \pm 0.07$
All Z and Atoll samples	$699.13 \pm 2.23$	$1.68 \pm 0.02$

\*: Data are taken from the references listed in Table 1.

**Table 1. List of LMXBs with the simultaneously detected twin kHz QPOs, together with the relevant quantities**

Source* name	$\nu_1^{(1)}$ (Hz)	$\nu_2^{(2)}$ (Hz)	$\Delta\nu^{(3)}$ (Hz)	$\langle\Delta\nu\rangle^{(4)}$ (Hz)	$\frac{\nu_2}{\nu_1}^{(5)}$	$\langle\frac{\nu_2}{\nu_1}\rangle^{(6)}$	$\nu_s^{(7)}$ (Hz)	$\frac{\langle\Delta\nu\rangle}{\nu_s}^{(8)}$	Refs.
<b>Millisecond pulsar</b>									
SAXJ 1808.4-3658	499	694 (725)	195	195	1.39	1.39	401	0.49	W
<b>Z source</b>									
Sco X-1	544-852	844-1086 (1130)	223-312	287	1.26-1.57	1.44	-	-	M,B,K
GX 17+2	475-830	759-1078 (1080)	233-308	282	1.28-1.60	1.46	-	-	B,K,P,1
GX 340+0	197-565	535-840 (840)	275-413	334	1.49-2.72	2.04	-	-	B,K,P,2
GX 349+2	712-715	978-985 (1020)	266-270	268	1.37-1.38	1.38	-	-	B,K,3
GX 5-1	156-634	478-880 (890)	232-363	318	1.38-3.06	2.05	-	-	B,K,P,4
Cyg X-2	532	857 (1005)	324	324	1.61	1.61	-	-	B,K,P
<b>Atoll source</b>									
4U 0614+09	153-823	449-1162 (1330)	238-382	322	1.38-2.93	1.57	-	-	B,K,P,5,6
4U 1608-52	476-876	802-1099 (1099)	224-327	287	1.26-1.69	1.44	619	0.46	M,B,K,7
4U 1636-53	644-921	971-1192 (1230)	217-329	286	1.24-1.51	1.35	581	0.49	B,K,P,8,9
4U 1702-43	722	1055 (1085)	333	333	1.46	1.46	330	1.01	K,P,10
4U 1705-44	776	1074 (1074)	298	298	1.38	1.38	-	-	B,K,P
4U 1728-34	308-894	582-1183 (1183)	271-359	327	1.31-1.89	1.50	363	0.90	B,K,P,6,11
KS 1731-260	903	1169 (1205)	266	266	1.29	1.29	524	0.51	B,K,P
4U 1735-44	640-728	982-1026 (1160)	296-341	313	1.41-1.53	1.45	-	-	B,K,P
4U 1820-30	790	1064 (1100)	273	273	1.35	1.35	-	-	B,K,P
4U 1915-05	224-707	514-1055 (1265)	290-353	338	1.49-2.3	1.71	270	1.25	B,K,P
XTEJ2123-058	849-871	1110-1140 (1140)	261-270	266	1.31-1.31	1.30	-	-	B,K,P

\*: Sources with the simultaneously detected twin kHz QPOs. However, we do not include XTEJ1807-294 because the discovery of its pair kHz QPOs was reported but unpublished (see e.g. van der Klis 2004). <sup>(1)</sup>: the range of  $\nu_1$ ; <sup>(2)</sup>: the range of  $\nu_2$ , the maximum measured  $\nu_2$  is shown in parenthesis; <sup>(3)</sup>: the range of  $\Delta\nu$ ; <sup>(4)</sup>: the average of  $\Delta\nu$ ; <sup>(5)</sup>: the range of the ratio of  $\nu_2$  to  $\nu_1$ ; <sup>(6)</sup>: the average of the ratio of  $\nu_2$  to  $\nu_1$ ; <sup>(7)</sup>: the spin frequency or the burst frequency identified as the spin frequency (see e.g. Strohmayer & Bildsten 2003; Muno 2004; van der Klis 2004, and references therein); <sup>(8)</sup>: the ratio between the averaged  $\Delta\nu$  and the spin frequency. W: Wijnands et al. 2003; B: Belloni et al. 2005, Belloni et al. 2002; P: Psaltis et al. 1999ab; K: van der Klis 2000, van der Klis 2004; M: Méndez et al. 1998, Méndez & van der Klis 1999, 2000. 1. Homan et al. 2002; 2. Jonker et al 2000; 3. O'Neill et al. 2002; 4. Jonker et al. 2002a; 5. van Straaten et al. 2002; 6. van Straaten et al. 2000; 7. van Straaten et al. 2003; 8. Di Salvo et al. 2003; 9. Jonker et al. 2002b; 10. Markwardt et al. 1999; 11. Migliari et al. 2003.